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EMPIRICAL PLATFORM DATA ANALYSIS TO INVESTIGATE HOW HEAT PUMPS OPERATE IN REAL-LIFE CONDITIONS

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ABSTRACT

Heat pumps have been widely acknowledged, by academia and industry, as highly efficient thermal energy technologies, for space heating and domestic hot water production. However, there is a lack of information about real performance in residential single family houses with active participation of end-users. In this paper, an analysis based on data from 242 heat pump installations in Denmark gathered over a period up to 4 years (2010 until today) is performed. COP, operating temperatures and socio-demographic data are used as basis for comparing theoretical and actual performance. Six different heat pump configurations are considered depending on source (ground or air) and sink (radiators, floor heating and/or combined systems). This unique study intends to point out the benefits and limitations of such technologies in terms of energy efficiency and comfort delivery, as well as investigating the suitability of heat pumps to support fossil-fuel free energy systems.

1. INTRODUCTION

The climate and energy targets set by the European leaders in 2007, known as “20-20-20” targets, involve 20% reduction in EU greenhouse gas emissions from 1990 levels; raising the share of renewable resources to 20%; and 20% improvement in energy efficiency (COM 2008). In Europe the energy demand in buildings accounts for 40% of primary energy consumption and 36% of CO_2 emissions. Currently, space heating (SH), cooling and domestic hot water (DHW) represent up to 70% of energy consumption in buildings (IEA 2013). To reduce emissions and improve energy efficiency, heat pump (HP) systems are increasingly deployed for heating, cooling and hot water supply in residential as well as commercial and institutional buildings. They have the potential to reduce the energy demand and CO_2 emissions by means of high energy efficiency and renewable energy integration. However, in order to fulfil the energy requirements these installations must have a Coefficient of Performance (COP) no less than the target stipulated by the energy authorities (Aggerholm 2013). Otherwise, they might jeopardize some climate and energy targets. This paper assesses the performance of real residential single family houses HP installations. The results are discussed in relation to implications of the interaction between HP installations as space and domestic hot water heating technologies and the future of the national energy system.

2. DATA BACKGROUND: *STYR DIN VARMEPUMPE* ONLINE PLATFORM

The platform *Styr din varmepumpe* (in English: Control your heat pump) consists of 280 households with HP installations which are equipped with sensors to monitor the HP operation, outdoor and indoor conditions. This platform monitors temperatures, fluid flows rates and electrical energy consumption.

2.1. Sensors

In order to measure fluid flows rates, inlet and outlet temperature of SH and DHW and HP electrical energy consumption, the installations are equipped with 7 temperature sensors, 2 flow meters and 1 power meter. The temperature sensors are PT1000-type sensors with four-wire connection and an accuracy class of 1/10 DIN, resulting in a tolerance of ±0.8˚C on the measurement value (35-60˚C). The flow meters have a tolerance of ± 4 % at average flow rates between 5 and 12 L/ min (Figure 1). The sensor data and the ON/OFF control commands are transmitted over an Internet connection to a server via a Linux-in-a-Box system. The sampling time of the communication link between HPs and the server is 5 minutes.

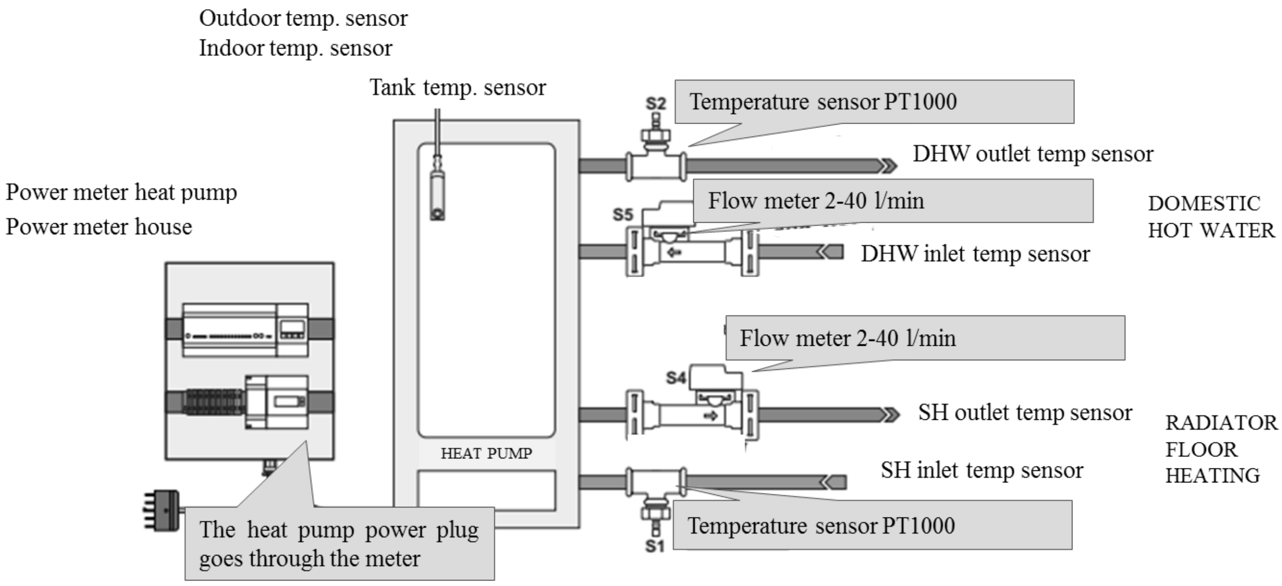

Figure 1. Schematic diagram of HP system with measuring points

2.2. HP installations

The households included in this platform all had heat pumps installed before being a part of the platform project, which started in 2010. The communication and sensor equipment have been subsequently installed, thus operational data is only available since 2012. In this paper, only 242 out of 280 available installations are considered due to missing descriptive data of the remaining 38 installations.

The houses are all real life inhabited households in different locations in Denmark. The houses size vary from small with a total heated area of 80 m^2 to larger houses with an area of 700 m^2 and the number of inhabitants ranges from 1 to 8. The average area is 183m^2 and the average number inhabitants per dwelling is 3. The construction year also varies, there are old houses built in the 1770s, other houses are newly built and some have been refurbished. Thus, the expected annual SH and DHW demand (Kragh 2010) in the households varies from 48 kWh/m^2 /year to 184 kWh/m^2 /year with an average 135 kWh/ m^2 /year.

Naturally, this heterogeneity yields to different HP heating capacities which range from 3 kW up to 40 kW. 80% of the installations are Brine-to-Water (B/W), with indirect closed loop horizontal ground source, while the others are Air-to-Water (A/W) based. There seems to be no clear relation between the heating capacity of the HP installed and the expected annual heat demand for each house – the latter is calculated based on Danish Building Research Institute statistics (Kragh 2010) and house area. In Figure 2 it can be seen, for example, that houses which have different heating demand (15MWh/year and 40MWh/year) are both equipped with 14 kW A/W HPs.

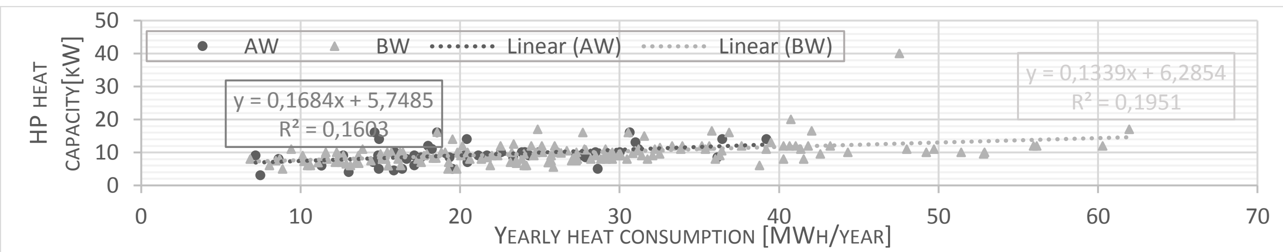

Figure 2. Relation between the HP heating capacity installed and the house annual heating demand

Most of HP installations (78%) have a heating capacity between 7 and 13kW (Figure 3).

Furthermore, residential installations HP configurations, vary in terms of the heat source and heat distribution system. As previously stated, the heat source can be air or ground based and the distribution system - which supplies the SH system – can be radiators or/and floor heating. In the scope of this analysis, the heat pump installations were divided in 2 main groups, related to the heat source: Air-to-Water (A/W) and Brine-to-Water (B/W), each divided in 3 sub-groups related to the heat distribution systems: Radiators (Rad), Floor heating (FH) and both, referred as combined (Combi). Figure 3 shows that the configurations of heating systems vary in the individual houses: 18% of the houses use FH while 20% have Rad and 63% have Combi. For Combi systems, the usual installation have the floor heating loop limited to the bathroom area.

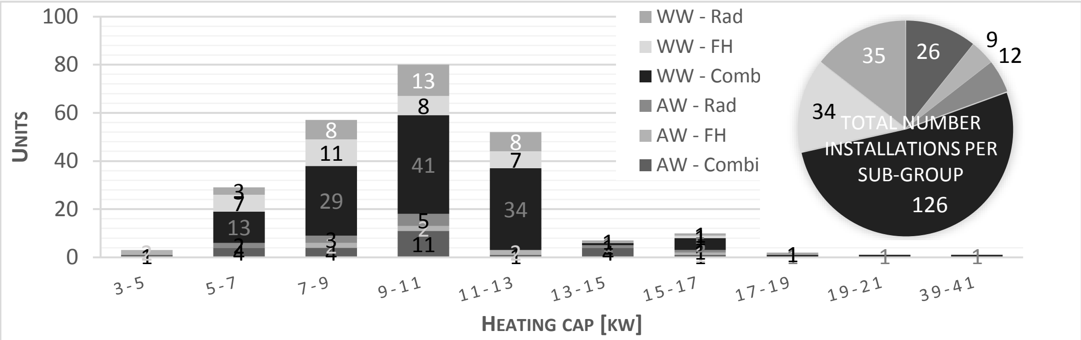

Figure 3. HP capacity installations distributed by installation type

Regarding the way HPs are connected to the SH and DHW distribution systems, Figure ***4*** shows the diagrams of the four different supply designs present in the platform installation:

- Design 1 Heat pump with tank for DHW storage (case for 43% of the installations studied)

- Design 2 Heat pump with double mantle storage tank (inner- DHW and outer- SH) (case for 17% of the installations)

- Design 3 Heat pump with buffer tank for both SH and DHW (case for 33% of the installations)

- Design 4 Heat pump with both DHW tank and buffer tank for SH (case for 7% of the installations)

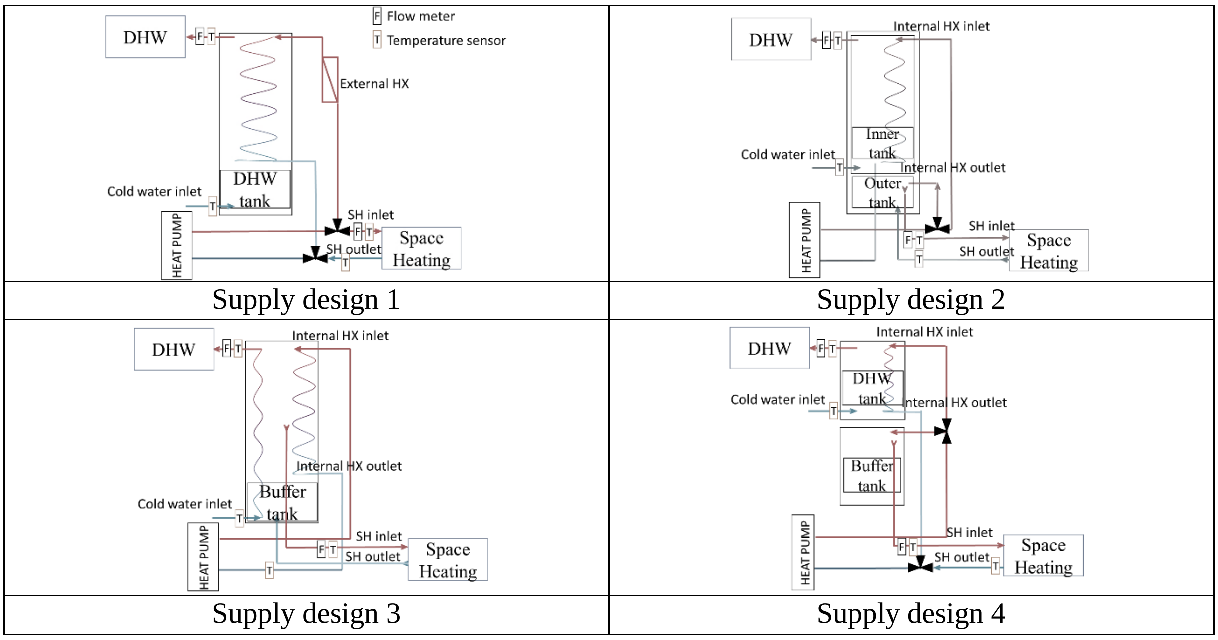

Figure 4. Diagrams of the different HP installation supply designs present in the platform installations and measuring points

In terms of water storage volume 42% of the installations have a tank between 150 and 200L (

Figure 5).

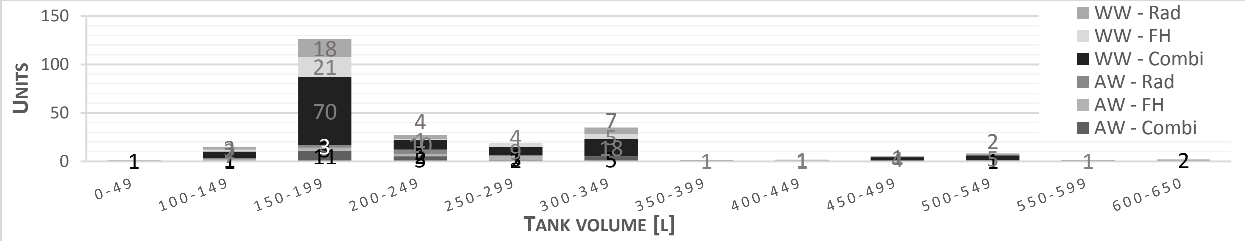

Figure 5. Water storage tank volume distributed by installation type

Additionally, it is important to state that some of the houses are equipped with other heating sources than the heat pump, for example a wood stove (44%) or solar heating (8%) or both (14%). Consequently, we are dealing with a realistic real life heterogeneous household portfolio which is representative of typical Danish households.

3. METHODS

This study is based on operational data gathered between 2012 and 2014. The data set will enable to assess the benefits and limitations of the HPs in terms of energy efficiency for SH and DHW supply as well as to assess the potential of this technology to integrate renewable power in the network.

The efficiency of HPs in real operation is defined by the Coefficient of Performance (COP) which is derived by the ratio of supplied heat (energy output) and the electrical energy demand (energy input) at different points of operation. Within this paper, the boundaries of the system considered for the input energy are the electrical energy demand by the compressor, the back-up electrical heater as well as the pumps for SH and/or DHW circuits. Both SH and DHW supplied are the thermal energy output. They are computed from the 5 min measured values by the flow meters and temperature sensors and averaged to each one hour. The SH and DHW inlet and outlet temperatures and the flow rate are measured directly after the water storage tank (see Figure *4*). The Seasonal Performance Factor (SPF) – which is the average annual of the COP measured – was computed in order to compare the real performance of HP installations with the one required by Danish Energy Authority (DEA) (Aggerholm 2013) to achieve the "20-20-20" energy goals.

Furthermore, the potential of these installations for load shifting is also included. The point of departure for the study of HP installations potential for renewable power integration is an analysis of the hourly electricity demand of the 280 installations. The current control scheme implemented in HPs prioritizes the DHW demand, i.e. in case there is demand for DHW at a specific time, the HP will always consume electricity with no chance for shifting electrical energy demand (Hudon 2012). Therefore, to estimate the real potential for load shifting, the electrical energy demand at times when only SH is supplied was studied. In other words, the current load shifting potential is here considered to be exclusively the SH load, when the electrical energy consumed for DHW demand is null. This partial potential is then compared to the total potential (SH+DHW demand) which can be enabled in case predictive control is implemented (like proposed in (Biegel 2014) and (Halvgaard 2013)). The total potential is given in an indicative way based on the 280 residential installations and scaled up to the expected number of HP installations in 2035 (in total, 196.000 A/W and B/W systems are expected to be installed (DEA 2013)). Finally, the number of operating hours in a day depending on the outdoor temperature (T_{out}) is discussed. These values were monitored by the electrical energy meter installed in each installation. The duration of these ON periods will define the actual flexible period of the installations. Here all the 280 HP installations were used for the analysis since no socio-technical data is needed for electrical energy demand analysis.

4. RESULTS AND DISCUSSION

4.1. Heat pump technology real performance in residential buildings

In this sub-section the operational conditions registered in the period between Jan. 2012 and Dec. 2014 at different outdoor temperatures are presented and discussed for the six different configurations of heat pumps.

Figure 6 shows the average operational temperatures in the space heating circuit and the COP for A/W installations in three different sub-groups corresponding to the different heat distribution system. It can be seen that the inlet temperature (T_{in}) increases with the decrease of outdoor temperature (T_{out}). The average T_{in} for A/W radiators systems is higher (40 ºC, max. 50 ºC) than both A/W FH (33 ºC, max. 37 ºC) and A/W Combi (38 ºC, max. 44ºC) installations. The COP varies with T_{out}. For Rad systems it ranges from 2.3 to 3.4, for Combi systems between 2.2 and 4.6 and, finally, of FH supply systems from 1.4 to 5.4. A ΔT (temperature difference between the inlet temperature and outlet temperature in space heating loop) two times higher than at T_{out} >-10 ºC explains such a low COP value for FH systems at T_{out} <-10 ºC.

In general, ΔT increases with decrease of T_{out} due to higher heat losses in the heating circuit. The ΔT is higher for the Rad systems (0.8 – 8.5 ºC) than for the other systems (0.6 – 6.3 ºC for FH and Combi) due to a larger thermal inertia of the latter. Nevertheless, at 7-9 ºC T_{out} a sudden increase of ΔT is observed and it decreases until 0-2ºC. This shows the effects of defrosting needs in A/W systems. When T_{out} goes below 7-9 ºC, A/W installations are forced to reverse the cycle occasionally to heat the outdoor unit in order to remove frost from the evaporator and allow the HP operation to continue. The ΔT decreases because the defrosting cycle disables the heating mode in the house side. This leads to a constant T_{in} at T_{out} between 0ºC and 10 ºC. Below 0 ºC, T_{in} increases substantially from 41 ºC at 0 ºC to 47 ºC at -4 ºC – in the case for Rad systems - and ΔT starts increasing again.

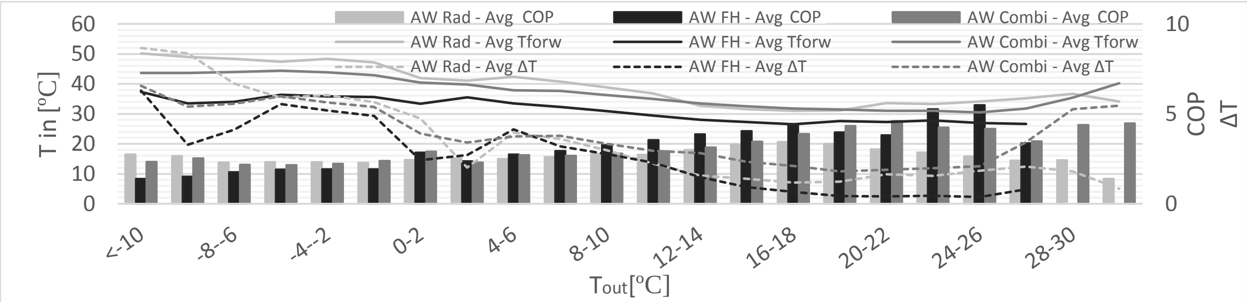

Figure 6. Typical inlet temperatures, ΔT and COP for A/W installations

In Figure 7 the operation temperatures and the COP in relation with the T_{out} for B/W systems are shown. Similar conclusions regarding the behaviour of the different heating supply systems can be drawn. Nevertheless it should be noticed that, as expected because of the nature of ground heat source, the COP of these installations is more constant than in A/W installations showing a smaller effect of the outdoor conditions in them. The COP of B/W Rad installations range between 2.6 and 4.4, B/W Combi installations between 2.3 and 3.3 and B/W FH installations between 2.4 to 3.4. Rad installations with ground heat source outperform A/W installations at any T_{out}, but A/W FH and Combi installations perform better than B/W installations at T_{out} higher than 10 ºC and 14 ºC, respectively. The following paragraph discusses in more detail the comparison between A/W and G/W COP differences.

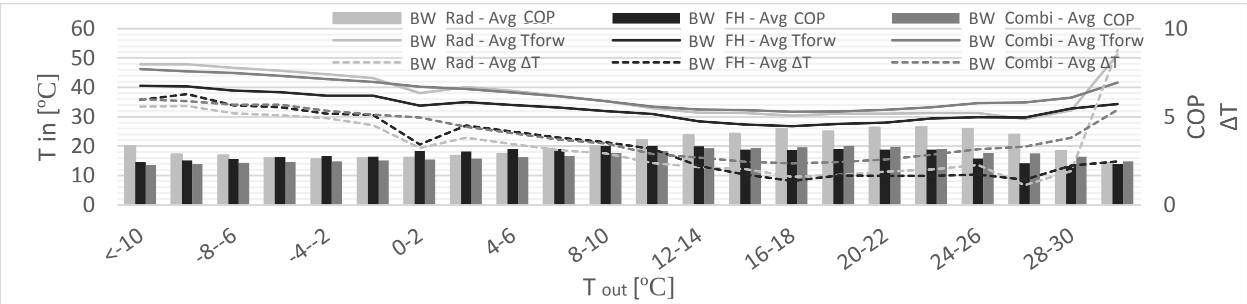

Figure 7. Typical inlet temperatures, ΔT and COP for B/W installations

In order to accomplish the aforementioned "20-20-20" energy targets (section 1), HP installations must provide energy in an efficient way as well as to support the integration of renewable sources in the national energy systems. According to the Danish Energy Authority (DEA) (Aggerholm 2013), brine/water heat pumps

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(geothermal heating systems) must have a nominal SPF no less than 3-3.7 if it supplies a floor heating and 2.6-3 if it supplies radiators (based on the standard DS/EN 14825 (H.Pedersen 2009). For A/W systems the required values are 2.7 and 3.2, respectively for Rad and FH. In Figure 8 the required nominal Seasonal Performance Factor (SPF) is compared with the SPF of the different systems during the year of 2012, 2013 and 2014 with an average annual outdoor temperature of 8.2 ºC, 8.4ºC and 10 ºC according to (DMI.dk 2015).

It can be seen that, in general, the performance of HPs in real conditions fulfils or exceeds the requirements, yet there are some exceptions. A/W systems with small heating capacity (<6kW) show a performance 14% lower than the required (2.7). The difference between the achieved and the required SPF in A/W systems is explained by a low average annual outdoor temperature (<10 ºC). Also, B/W FH with a capacity >6kW have a SPF of 3.2, i.e. 15% lower than expected, this is explained by the high required value (3.7). Furthermore, it can be concluded that lower capacity (<6kW) B/W installations have an average SPF between 3 (Rad) and 3.2 (FH), this is up to 29% higher than similar A/W systems. Among larger capacity (>6kW) the average SPF of B/W installations is only up to 8% higher than A/W. Notice that because the requirements for HPs are only given for Rad and FH systems, Combi systems are here considered as Rad. Unfortunately, no operational data was available for the year of 2014 for A/W FH 3-6kW installations, thus no conclusion can be drawn of their performance in 2014.

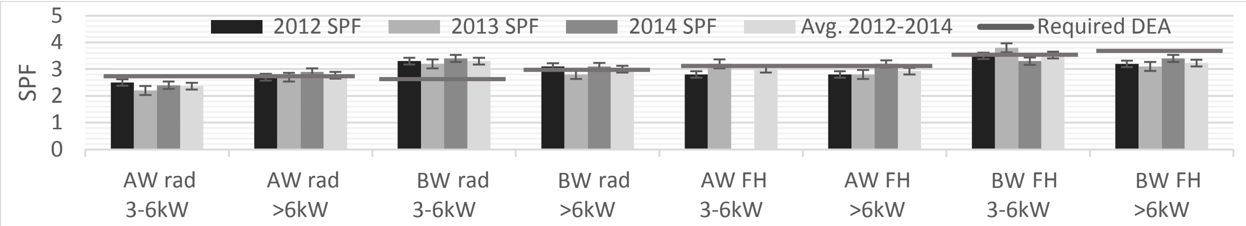

Figure 8. Comparison between real and required nominal power factors (Aggerholm 2013)

Finally, the performance of different HP supply designs is also analysed based on the operational data available from 2012 to 2014. Four different types of hot water storage configurations were considered, designs 1, 2, 3 and 4 as described in sub-section 2.2. Taking into account the average SPF 2012-2014 for all HPs, it is clear that HP systems which have two hot water tanks - one for DHW storage and another buffer tank for SH storage (design 4) - can achieve performances up to 25% higher than other designs with the same HP source and sink (case of AW Rad). Systems equipped with a buffer tank or double mantle tank– design 1 and 2 - also perform well, their SPFs are only 2-3% smaller (Grand Total) than installations equipped with design 4. The A/W FH configurations are only available in two designs (design 1 and 3) and B/W FH only three (design 1, 2 and 3). Therefore there were no data for other designs analysed.

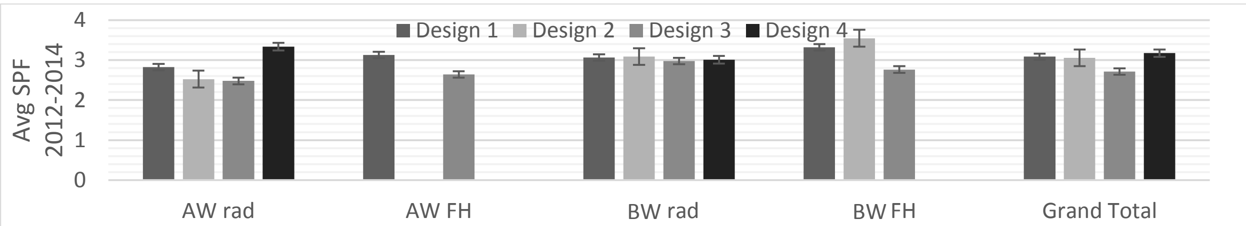

Figure 9. Performance comparison of the different types of installations sorted by the 4 supply design cases

4.2. Heat pump potential for renewable power integration

In this section, the potential for non-dispatchable renewable power integration is assessed. From the perspective of the grid, load management can contribute to the security of supply if it is available in critical grid situations, also called ancillary services. These situations are more frequent in energy systems based on stochastic renewable power supply. HP installations have potential to provide these services by managing the SH demand and/or DHW production. These services are delivered by reducing the system-wide peak load or by providing balancing energy or covering re-dispatch.

In Figure 10 the daily required time to ensure the heat needs are covered is presented in relation to T_{out} as well as the number of start-ups. The ON period and the number of start-ups (# start-ups) doubles at around T_{out} =14 ºC with respect to T_{out} >14 ºC and continues to rise with the decrease of T_{out}. It can be seen that especially A/W FH installations at T_{out} =0 ºC decrease their ON time even though there is sudden rise in number of start-ups at that temperature due to defrosting cycle. Fundamentally, Figure 10 shows the time frame potential for load management range that can be expected for HP which varies from 22 hours with T_{out} >14 ºC to 1 hour in cold days (T_{out} < -10 ºC). The difference between the number of average ON periods A/W installations and B/W is not significant. Their average ON period duration is 8,1 hours and 7.5 hours, respectively.

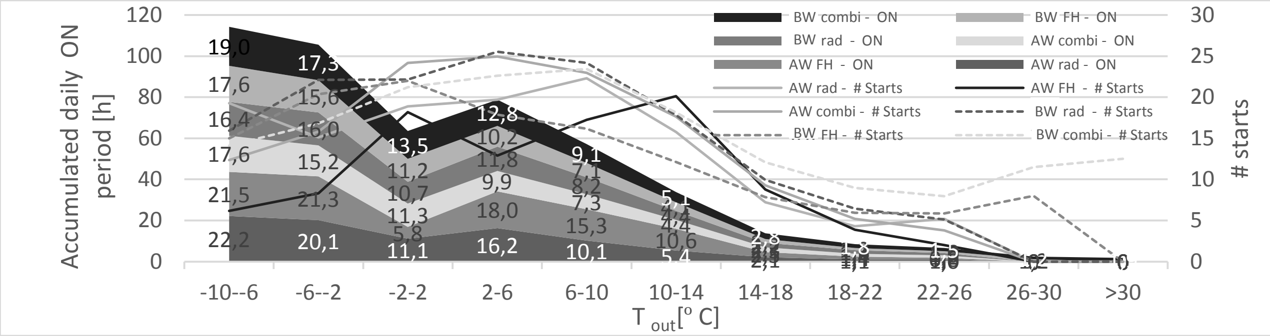

Figure 10. Daily operating hours and number of start-ups of HP installations vs. the outdoor temperatures (T_{out})

The distribution of the outdoor temperatures is shown in Figure 11 where data from the year 2013 is used as an example. This figure shows the energy demand - Total EL -by the 280 HPs as well the stand-by load – EL stand-by - and the power load exclusively for SH demand – SH EL. In 2013, the 280 residential HP installations can offer a maximum interruptible load up to 519 kW for a specific hour (see Figure 11 – January, 25th) if both SH and DHW demands can be shifted and a minimum of 25 kW (July, 27th). Nevertheless, with the current heat pump installations control, the real power range available for load management in Jan, 25th goes only up to max. 287 kW (55% of the total amount) and a minimum 9 kW (July, 27th), as explain in Section 3, this is the demand that corresponds uniquely to the SH demand.

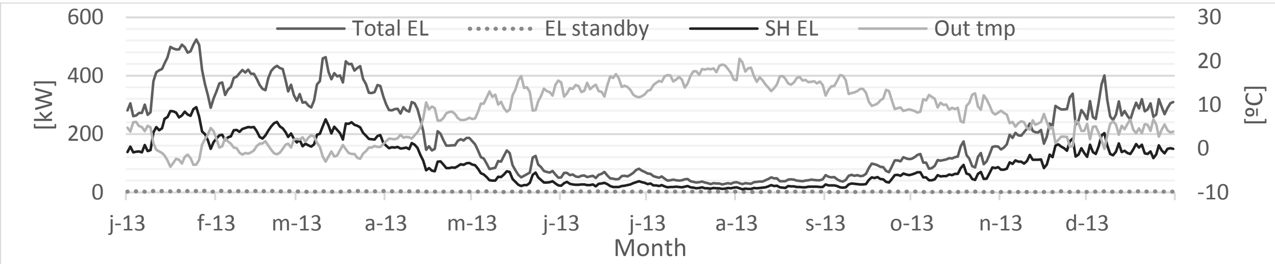

Figure 11. Hourly electrical power demand of 280 HPs installations and outdoor temperatures in 2013

The load management could be improved with a control based on weather and demand forecast, where the sensible thermal storage potential is also taken into account. If implemented the total electricity demand of the HPs will be available for load management, this will mean that the load management potential in terms of max. power can be increased 80% from 287 to 519 kW and 84% in terms of energy from 40.4 MWh to 74.18 MWh in 2013. Furthermore the frequency of availability for load management can increase from 300 kW once a year to at least 300 kW 33% of the time of the year (Figure 12). The frequency of load management potential for 2012 and 2014 is also shown for comparison.

Scaled up to the 196.000 HPs A/W and B/W installations expected by 2035 (DEA 2013) the power available for load management will correspond to a total electrical power potential of around 359 MW (deducting the stand-by demand). If this is the case, according to Hedegaard (2012), 14% of the consecutive negative net load (excess electricity) below hundreds of MW with a duration up to one day could be balanced with HPs in energy systems with a high-share of wind power and thus HPs installations show to be capable of integrating more renewable energy.

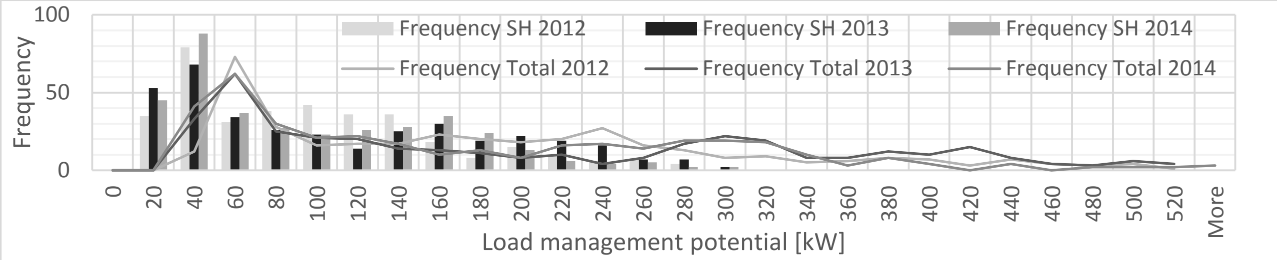

Figure 12. Frequency of Total and SH interruptible load available from 2012 to 2014

5. CONCLUSIONS

This paper analyses the performance of 242 real residential heat pump (HP) installations located all over Denmark considering energy efficiency (COP and SPF) and load management potential to increase the share of non-dispatchable renewable energy in the national energy mix. Six different types of configurations are considered according to the heat source and heat distribution system.

According to the data measured during the period of Jan.2012-Dec.2014, the HP installations can perform as recommended to achieve the "20-20-20" goals. They have a SPF that ranges between 2.4 and 3.5, depending on heat sink/source temperatures and installed capacity. It is shown that small capacity (<6kW) A/W HP systems cannot achieve the expected performance if the average annual outdoor temperature is lower than 10ºC.

In addition, an analysis of four different HP supply configurations is done. The configurations that showed better performance, are installations with two storage tanks, one dedicated to DHW storage and a buffer tank for SH storage. HP installations with same heat source and sink if equipped with such design can have their SPF improved up to 25% when compared to other designs. Furthermore, it is shown that double mantle tanks and buffer tanks for DHW can also improve the efficiency 22-23% when compared to similar systems equipped with buffer tanks for both SH and DHW.

Finally, the assessment of the potential of HP for renewable power integration shown that to harvest the full load management potential of residential HP power demand, the current HP operational controls have to be replaced by more complex controls. It was assumed that HPs installations, supported by the thermal inertia of the buildings and sensible heat storage, have a load shifting potential that varies from 2 to 22 hours depending on the outside temperature. Results show that in a future scenario, where 196.000 HP installations are expected to be installed in Denmark, the total maximum load management of residential heat pump installations will be 359 MW.

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NOMENCLATURE

A/W	Air –to-Water	[-]
Combi	Combined system, both radiators and floor heating	[-]
COP	Coefficient of System Performance	[-]
DHW	Domestic hot water	[-]
EL standby	Electricity demand of HPs when OFF	[kW]
FH	Floor heating	[-]
HP	Heat pump	[-]
$\mathbf{T_{out}}$	Outdoor temperature	[ºC]
Rad	Radiators	[-]
SFP	Seasonal Performance Factor	[-]
SH	Space Heating	[-]
$\mathbf{T_{in}}$	Inlet temperature	[ºC]
Total EL	Total electricity	[kW]
B/W	Brine-to-Water	[-]